MEASUREMENT OF THE SPECTRAL ABSORPTION OF LIQUID WATER IN MELTING SNOW WITH AN IMAGING SPECTROMETER

Robert O. Green[1,2] and Jeff Dozier[2]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
[2]University California at Santa Barbara, CA 93106

1. INTRODUCTION

Melting of the snowpack is a critical parameter that drives aspects of the hydrology in regions of the Earth where snow accumulates seasonally. New techniques for measurement of snow melt over regional scales offer the potential to improve monitoring and modeling of snow-driven hydrological processes. In this paper we present the results of measuring the spectral absorption of liquid water in a melting snowpack with the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS).

AVIRIS data were acquired over Mammoth Mountain, in east central California on 21 May 1994 at 18:35 UTC (Figure 1). The air temperature at 2926 m on Mammoth Mountain at site A was measured at 15-minute intervals during the day preceding the AVIRIS data acquisition. At this elevation, the air temperature did not drop below freezing the night of the May 20 and had risen to 6 degrees Celsius by the time of the overflight on May 21. These temperature conditions support the presence of melting snow at the surface as the AVIRIS data were acquired.

2. OPTICAL PROPERTIES OF LIQUID WATER AND ICE

The basis for the spectral measurement of liquid water is derived from the optical properties of liquid water in the 400- to 2500-nm range. To spectrally measure liquid water in snow, its absorption must be separable from the absorption due to frozen water. The complex refractive indices (Warren, 1982; Kou et al., 1993) were used to model the spectral properties of liquid water and ice. The complex refractive indices of these two phases of water are similar in overall magnitude and spectral trend. However, in detail these physical constants differ due to the different molecular bond energies of water in the liquid and solid state.

To investigate the contrast in spectral absorption between liquid water and ice, the transmittance of a 10-mm path through these materials was calculated (Figure 2). The spectral absorptions are overlapping, but displaced in both the 1000- and 1200-nm spectral regions. The 1000-nm spectral region is selected for this research because snow is more reflective at these wavelengths and path lengths of 10 mm are expected in the snowpack (Dozier, 1989).

3. AVIRIS MEASUREMENTS AND TRANSMITTANCE MODEL

AVIRIS measures the upwelling spectral radiance from 400 to 2500 nm at 10-nm intervals and collects images of 11 by up to 1000 km at 20-m spatial resolution. AVIRIS radiance spectra acquired over Mammoth Mountain were inverted to apparent spectral reflectance (Green, 1990; Green et al., 1993). An equivalent path transmittance model was developed for liquid water and ice in the 1000 nm spectral region. The model was inverted using a nonlinear least squares fitting routine to derive the equivalent path length transmittance of liquid water and ice for each spectrum measured by AVIRIS. A linear spectral albedo term is included in the model to compensate for illumination. For the AVIRIS spectrum in open snow below and adjacent to site A, the inverted spectral model returned values of 1.9 ± 0.1 mm liquid water and 13.3 ± 0.7 mm ice (Figure 3). The presence of liquid water due to surface melting at this elevation is consistent with the temperature prior to the AVIRIS acquisition. For site B to the north of the summit of Mammoth Mountain, the inverted model returned equivalent path transmittance of 0.0 mm liquid water and 20.1 ± 0.9 mm (Figure 4). At the 3362 m summit, the temperature is calculated to be 2.6 degrees Celsius colder. Snow at these higher elevations and north facing slopes had not commenced surface-melting at the time of AVIRIS data acquisition.

This equivalent path transmittance model was inverted for the entire AVIRIS scene of Mammoth Mountain (Figure 5). Absorption due to ice in snow is measured at Mammoth Mountain and to the higher elevations in the northwest. At this late spring date, absorption due to ice was not measured at the lower elevations to the east and in the valley to the west of the mountain. The equivalent path transmittance due to liquid water was derived for the AVIRIS scene (Figure 6). Liquid water is measured in the AVIRIS spectrum in the snow at the lower elevations at Mammoth Mountain. As expected, liquid water is absent at the highest elevations of Mammoth Mountain where the snow is fully frozen. At low elevations, liquid water is also measured in the leaves of vegetation (Green et al., 1991). Liquid water in melting snow is spectrally distinguishable from liquid water in vegetation, based either on the absorption of ice in snow or chlorophyll in vegetation.

4. CONCLUSION

Examination of the optical constants of liquid and solid water shows that in the 1000 nm region these two phases of water are separable, based upon their spectral properties. Measurement of these two phases of water requires spectral modeling of the overlapping absorptions of the liquid water absorption centered at 970 nm and the ice absorption at 1030 nm. An equivalent-path transmittance model was developed for liquid water and ice. This model was inverted using a nonlinear, least-squares spectral fitting approach for Mammoth Mountain AVIRIS data. Liquid water and ice were measured in melting snow below 2926 m based on spectral properties. Near the summit at 3362 m, only the absorption due to ice was measured. The occurrence of fully frozen snow at high elevations and melting snow at intermediate and low elevations is consistent with measured temperatures and elevations at the time and date of the AVIRIS acquisition.

This first-time remote measurement of the spectral absorption of liquid water in a melting snowpack will lead to new algorithms for the measurement, modeling and monitoring of snow-driven hydrological processes.

5. FUTURE WORK

Future research will focus on development of a radiative transfer model of the snowpack when both the liquid and solid phases of water are present. In 1995 additional AVIRIS flights with in situ measurements will be used to further validate the measurement of these two phases of water in the snowpack.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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8. FIGURES

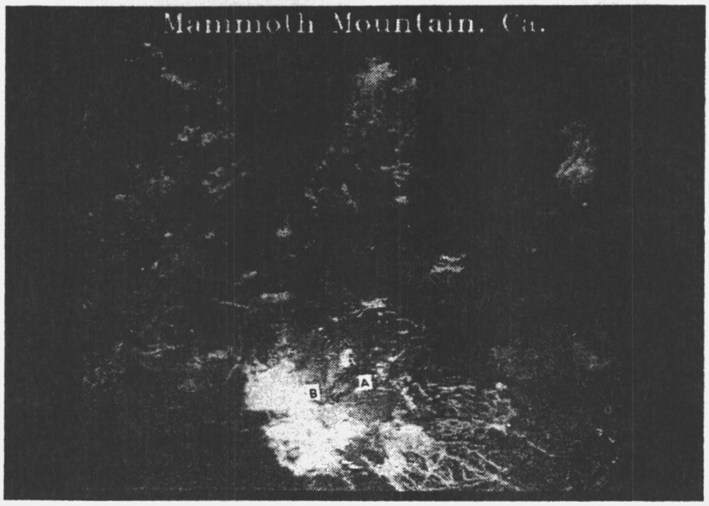

Figure 1. AVIRIS image of Mammoth Mountain with ski runs in the lower center of the image. North is to the top. (See AVIRIS Workshop Slide 4.)

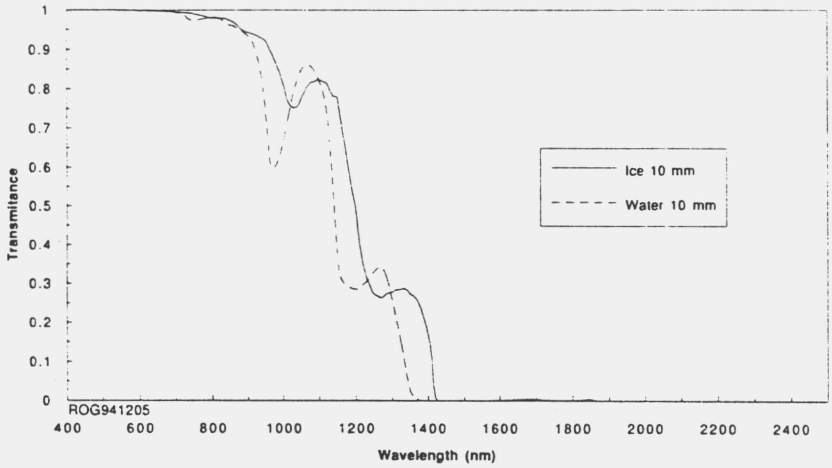

Figure 2. Transmission of light through 10 mm of water and ice.

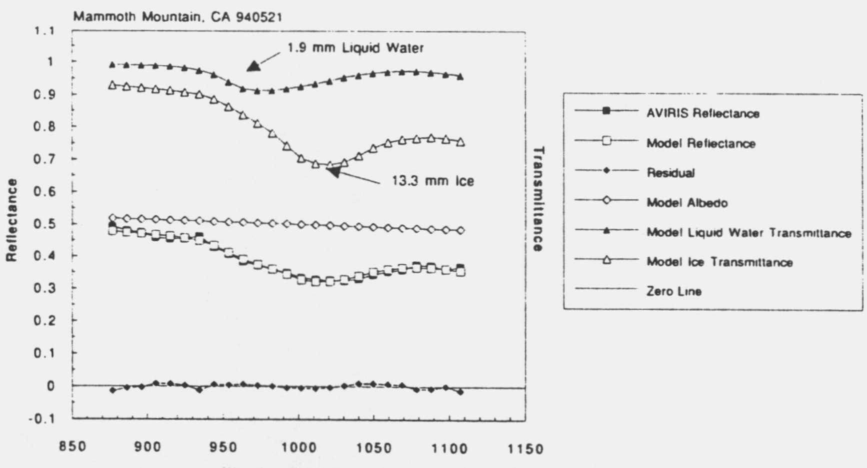

Figure 3. For site A at Mammoth Mountain, CA, the AVIRIS-measured spectrum and modeled spectrum when both liquid water and ice are present. Also shown is the residual disagreement and components of the model.

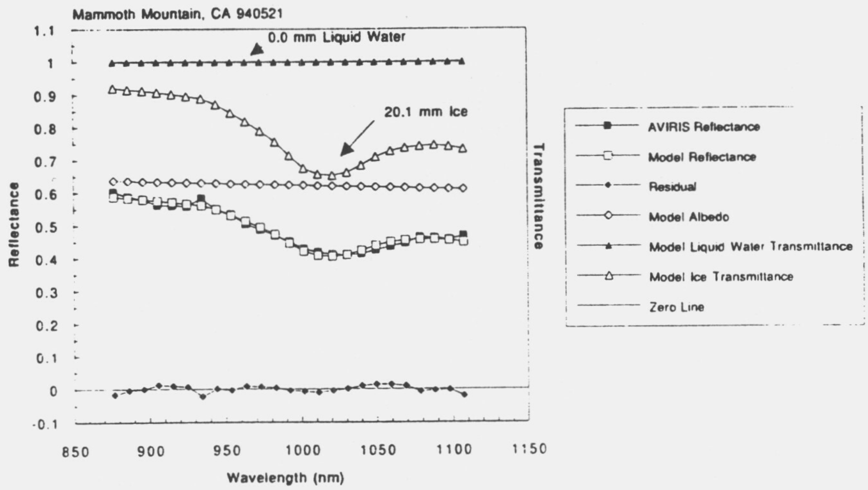

Figure 4. For site B, the AVIRIS-measured spectrum and modeled spectrum when ice is present. but liquid water is absent.

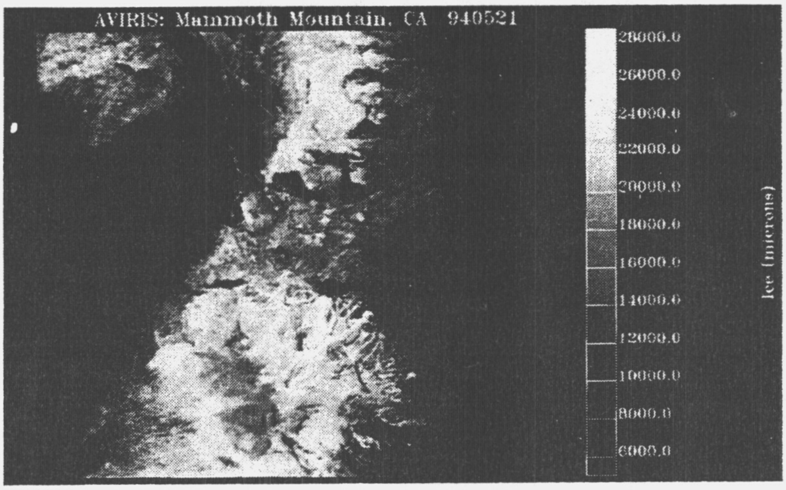

Figure 5. AVIRIS-derived path equivalent transmittance image for ice at Mammoth Mountain, CA. Ice is present only on the higher elevation in the May data set. (See AVIRIS Workshop Slide 4.)

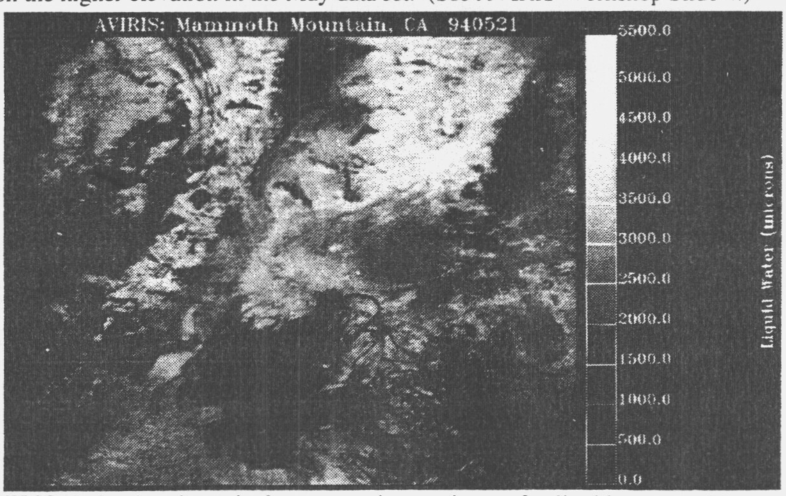

Figure 6. AVIRIS-derived path equivalent transmittance image for liquid water at Mammoth Mountain, CA. Liquid water is present on the lower snow slopes of the mountain where the snow is melting. Liquid water is also measured in healthy vegetation. (See AVIRIS Workshop Slide 4.)